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How much desert does a car need?

The case for more intensive research into the utilization of solar energy

Les besoins en désert d'une voiture?

Playdoyer pour une recherche plus vigoureuse dans l'utilisation de l'énergie solaire

Wieviel Wüste braucht ein Auto?

Ein Plädoyer für eine nachdrücklichere Erforschung der Sonnenenergienutzung

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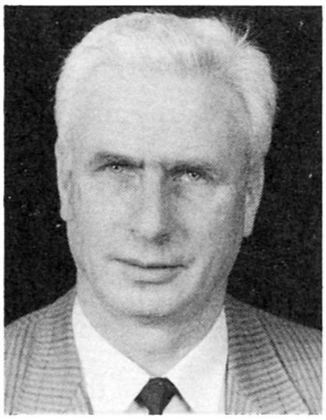

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SUMMARY

The only answer to the greatest threat in the history of mankind – the **population explosion** with undignified poverty in large areas of the world and, as a result of that, climatic and **environmental catastrophes** all over the world – is a clean, safe source of energy available in sufficient quantities for all of mankind. It would be both technically feasible and affordable – a fraction of the earth's desert areas would be enough to obtain **from solar radiation** the amount of energy needed to avert these catastrophes. Mankind and nature will both benefit from each additional percentage of our energy demand we obtain from the sun. In the annex solar chimneys and metal membrane concentrators with Stirling engines are briefly described.

RÉSUMÉ

Une source d'énergie propre, sûre et disponible en quantité suffisante pour toute l'humanité! Voilà l'unique réponse à la plus grande menace dans l'histoire de l'humanité: **l'explosion démographique,** accompagnée d'une pauvreté indigne de l'homme sur de vastes zones de la planète et de **catastrophes écologiques** et climatiques dans le monde entier. Il serait possible aussi bien du point de vue technique que financier d'obtenir à partir **du rayonnement solaire** la quantité d'énergie nécessaire pour écarter ces menaces, et une partie infime de la surface des déserts du globe y suffirait. L'homme et la nature seront les bénéficiaires de chaque pourcent d'énergie supplémentaire tiré du soleil. Une annexe décrit des cheminées solaires et systèmes de récupération d'énergie solaire.

ZUSAMMENFASSUNG

Eine allen Menschen in ausreichender Menge verfügbare saubere und sichere Energiequelle ist die einzige Antwort auf die grösste Bedrohung in der Menschheitsgeschichte: **Bevölkerungsexplosion** mit menschenunwürdiger Armut in weiten Teilen der Welt und als Folge davon Klima- und **Umweltkatastrophen** auf der ganzen Welt. Es wäre sowohl technisch möglich als auch finanzierbar, und es reichte ein Bruchteil der Wüstenflächen der Erde aus, um die zur Abwendung dieser Bedrohungen nötige Energiemenge **aus der Sonnenstrahlung** zu gewinnen. Jedes zusätzliche Prozent unseres Energiebedarfs, das wir uns von der Sonne holen, entlastet Mensch und Natur. – Im Anhang werden das Aufwindkraftwerk und Metallspiegel mit Stirlingmotoren kurz beschrieben.

Before going on to read the following pages, dear reader, try to answer for yourself the question put by the title above. Is it possible to fulfil the dream of the exhaust-free car, of the clean city, with solar energy? Is there so much desert on this earth that we could procure these quantities of solar energy and transport them here, and so that we could do without oil, that polluting and exhaustible fuel? Would it even be possible in principle to substitute solar energy for all other sources of energy available today - such as coal, gas, uranium - in so far as they do not, unlike hydropower, already more or less meet all the reasonable requirements for an energy source of the future?

Imagine solar power stations in the Sahara - atmospheric power towers, concentrating mirrors, solar cells, transforming the sun's rays into electricity. This is then used to split water, by electrolysis, into its component parts hydrogen and oxygen. This hydrogen is then transported here and takes over the role of petrol and diesel fuel. Hydrogen-driven engines do not produce any harmful exhaust, but burn hydrogen together with the oxygen in the air to produce clean water. A slight whiff of washing machine is all that comes out of the exhaust pipe.

To return to our question: how much desert area does a car-owner need to be able to procure enough hydrogen to drive 15,000 kilometres per year here in Germany?

Once you have the answer, all you have to do is to multiply that area by 26.7 million, thus converting all the motor traffic in the Federal Republic of Germany to clean hydrogen. We need an area of desert 4.4 times greater than that required by Federal German motor traffic to meet our total energy demand, and we need 29 times the latter figure if we want to take today's global energy demand from the sun. Of course, that would be an immense area. How big do you think it would be? Do you think the Sahara would be big enough?

If several times the Sahara were needed, then things would not look good; if the result were an area smaller than the Sahara, or even much smaller, and if we could afford this energy, then we could draw at least part of our energy demand from the sun and we would have a chance of solving the greatest material problem in the history of mankind, that of the permanent inhabitability of the earth. Of course, there would still be the immense political task of concluding long-term treaties with the sunny countries. The unpredicted political events of the past few months justify the assumption that even this could work. All the world's inhabitants would benefit.

THE THREAT

Energy is the material key to human life on this planet. That may well sound banal, but as members of a wealthy industrial country who judge everything only in terms of its present cost and for one legislature period, we are scarcely aware that, while we still have the energy we need at our disposal, its distribution, from a global point of view, is even now neither right nor just.

This is why untold problems have mounted up over the last few decades, problems which - and that is truly incredible - we are all aware of, yet we neither shout out nor do we do what has to be done:

- Pollution

When wood and straw, or fossil fuels like coal and oil, are burned, and when trees are felled, trace gases and pollutants are set free - carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrous oxides (NO_x) and ozone (O_3), chlorofluorocarbons, heavy metals, and, as has been somewhat forgotten recently, a lot of waste heat.

Even if all the correlations are still not known today, and even if measurements are still incomplete, no one denies the danger of the greenhouse effect and everyone is aware of today's catastrophic environmental damage from his own experience:

In the case of the greenhouse effect, even cautious estimates assume that if the present trend continues we can expect an average rise in temperature of 3°C in about fifty years' time. The result will be great regional changes in climate, with more aridity in certain places and more rain in others.

In the case of direct damage to nature, prognoses are no longer necessary. The dying forests, the dying fish and, more recently, the threat to drinking water are talked about everywhere, and there is no longer any doubt that acid rain and an increased concentration of ozone at higher altitudes are the cause. Of course, these are not solely due to combustion, but equally to industrial pollutants. While a lot is being done here in Germany to preserve clean air, and the catalytic converter has become perfectly commonplace, a look over our borders, at the dead forests in the Erz- and Riesengebirge for example, will tell us that we do not even have to go to the developing countries in order to realize that, for economic reasons, there is still a long way to go before globally effective environmental protection is achieved, and that we have to come to grips with this evil at its root - fuel itself.

Although it may be a cause of joy, when looking at the architecture of the last few decades, to see that steel and concrete cannot survive in their aggressive environment, we simply cannot accept the fact that this stone evidence of the human architectural heritage has, in recent decades, been more eroded, corroded, literally dissolved and eaten up by the air and the rain than used to be the case in centuries or millennia. Soon, our cultural history will only exist on paper.

The only energy we can afford is clean energy!

-The exhaustion of resources

In a few decades we consume, or rather waste, raw materials that are the product of millions of years; in other words, that are irreplaceable for mankind. It is irresponsible to burn mineral oil in cars if one knows that later generations will be without it for chemical or pharmaceutical purposes. Even with production continuing unchanged at present levels - and the only person capable of wanting that is someone who selfishly thinks of us and continues to keep the majority of mankind away from the least necessary amount of energy (see below) - mineral oil will only last about another 35 years, natural gas 50 years, coal 250 years, uranium (without fast breeders) 80 years. If so-called "reserves" are included - further deposits which are difficult to mine and are thus unprofitable by today's standards - then the situation looks somewhat more favourable. However, the figures unequivocally show that rapid decisions are needed if we do not want to have consumed all the fossil fuels including uranium but excepting coal (which is particularly polluting) within about 60 years; that is, unless nuclear fusion, against all expectations, proves to be feasible after all. Do we want to rely on that?

We can only consume what belongs to us: in other words, we can only use renewable sources of energy!

-Nuclear energy

When energy is generated from nuclear power, CO_2 is not given off; since the latter shares roughly one-half of the responsibility for the greenhouse effect, this gives nuclear power an advantage over coal- or oil-fired power stations. Even in the case of nuclear power, however, irreplaceable raw materials are burned up and 65% of the energy produced is wasted. This exhaust heat, either as steam or because it increases the temperature of rivers, is a burden on the environment. In addition, the use of nuclear energy for military or energy purposes has led to a considerable increase in the proportion of radioactive trace gases in the atmosphere, yet we still do not know whether this will have any effects. Nuclear fusion would not improve this situation.

Even assuming that we were to succeed in making safe these complex systems that are too involved for a single individual to have a clear view of everything that is going on inside them, and if we accept all the breakdowns and accidents that have happened so far as unavoidable childhood illnesses, the thought that nuclear power plants should be exported to technologically less developed countries is a chilling one. The export of a chemical-weapon factory is a petty offence in comparison. Last June, according to official figures, reactors had to be shut down unexpectedly 19 times in the Soviet Union alone, and almost all of these incidents could be traced to human error and sloppiness. If even we (i.e. those who developed these systems for themselves) have difficulties and still cannot agree about re-processing and disposal, how can we expect countries, where not even a car is repaired decently, to observe all the relevant safety and environment standards? To avoid the risk of fuel rods accidentally landing on a rubbish dump, the manufacturers of nuclear power stations would have to watch over their maintenance, thus forcing these countries into a new colonial dependence.

If one considers that nuclear power only contributes a little more than 2% of the current total world energy supply, and how much money it has swallowed up through shutdowns alone, then one really has to ask whether this was and is worth all its negative effects. Rightly or not, it has undermined faith in modern technology, without which we cannot live, has cast doubt on the reliability of political claims and, above all, has spread fear and dread and permanently disturbed domestic peace.

Finally, and most importantly, with nuclear power stations all over the world, how could the military misuse of plutonium for bomb production be prevented? Bank robbery, too, only became possible as a result of bank branches spread all over the country: nobody ever broke into the Treasury.

We need power stations that can be operated safely by all people over the world! Anybody should get command of only such power plants which he can operate safely and responsibly.

-Population explosion - energy deficit

The threat to mankind posed by the existence of the atom bomb is slight - and not only since the recent gratifying, if not almost incredible, change in the global political scene - in comparison to the consequences of a continuing increase in population. Even the comparatively harmless problem of people seeking asylum is an example of the complicated and multi-layered manifestations of this threat. It is clear that energy consumption, pollution and the number of people on earth are mutually dependent.

While our population is not on the increase and that of the industrial nations as a whole is only increasing slightly, certain African, Asian and South American nations have annual rates of growth of more than 3%, and double roughly every 20 years. Today's world population is almost five billion (thousand million). Over the centuries, it increased very slowly - in the thousand years before Christ's birth, for example, from 80 to 160 million. Since the industrial and medical revolution, the period needed for such a doubling has fallen from 150 to 100 years, and finally to 35 years, or one generation! Easy to calculate, but difficult to imagine how things will progress in the Third World, where even today every development, let alone advance, is swallowed up by the increase in population. Indonesia would need economic growth of 9-10% just to maintain its present miserable economic situation.

Of course, predictions about the future development of the world's population differ greatly. However, all agree that the population increase in the developing countries will be greatly reduced in the next century as a result of similar factors to those we have experienced in industrialized societies, and will finally reach a standstill towards the end of the next century, once a figure of some 10 to 12 billion has been reached - wishful thinking?

What is clear is the direct relationship between a great increase in population and low energy consumption or a low standard of living. At today's global primary energy* consumption of some 10 TWa/a** (or 11,000,000,000 t coal equivalent p.a.) by 5 billion people, the average individual has more than 2 kWa/a at his disposal.

Personal transport consumes a particularly great amount of energy - a middle-class car (as long as it is driven) uses roughly 50 kWa/a. However, a considerable part of the energy we need is not directly available to us, but we use it unnoticed in the form of goods and objects whose production requires energy. In Germany, about 47% of our final energy* is consumed by households and small-scale consumers, 29% by industry and 24% by transport.

In fact, however, some 75 % of today's world population cannot even afford this very low average of 2 kWa/a, while others waste energy. Today, industrial nations, which contain 25% of the world's population, account for about 75% of global energy consumption.

An American has a pro capita consumption 24 times (11 kWa/a), a European 9 times (4 kWa/a), and a Chinese 1.5 times (0.64 kWa/a) that of a South-East Asian or African (0.45 kWa/a). By the way, Russians and East Germans use more than twice as much as Western Europeans. In view of their real standard of living this can be due only to their low efficiency.

In reality, however, nothing at all ever reaches the countryside in developing countries. By the time we have eaten breakfast and got to work, we have consumed more energy than a Nepalese in a whole month. We consume more than a thousand times as much as he does. And what is worse is that they have to meet their requirements by gathering wood. If this takes the whole day and after the countryside is deforested, the soil is eroded in consequence, and rain does not come, then children remain as the only life insurance and people flee to the cities. In this way, the populations of Mexico City, Cairo and Teheran have increased ten-fold over the past 30 years and not only in Calcutta are there indescribable slums, but also in Stuttgart's twin city Bombay, in which millions of children vegetate without a future.

One would have to be blind in order not to realize that the few people seeking asylum, who have already been inflated into a problem, are nothing other the first bubbles of steam from a cauldron which is soon going to explode. If we permit ourselves the right to barricade ourselves in our citadels of prosperity, then we should at least do our part to offer those out there a prospect other than poverty or flight, or we should at least recognize that their present way of meeting their energy demand, deforestation and burning wood, is destroying our common

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* Primary energy is obtained in the form of coal, natural gas, uranium, crude oil, sun, water, etc., transformed at an average loss of 30% into final energy forms such as domestic coal, electricity, petrol, domestic gas, etc., 50 % of which (a final figure of one-third of primary energy) is really utilized as usable energy in the form of room heat, process heat, transportation or light. The latter transformation varies extremely, between 0% loss for electricity in a heater and 80% for fuel in a car.

**Instead of the still frequently used old unit of kilograms of coal equivalent per annum, I shall use here the more modern and equally understandable kWh/a (kilowatt-hour per annum), or, since global energy consumption involves such a gigantic quantity, the TWa/a (terawatt-years per annum) = 10^9 kWa/a (1 billion kilowatt-years per annum).

environment. Of course, the causes of this development are complex and cannot solely be explained, let alone resolved, by the relationship between energy consumption, living standard and number of children. By no means, because we would find ourselves in a vicious circle (see below) as a result, should the case be put forward for helping Third World countries to a development that is as energy-greedy as ours. But to live decently without any energy is impossible, and if the oil bills eat up the foreign exchange needed for industrial investment and artificial fertilizers, which are needed because natural dung is being burnt for lack of wood, then development out of poverty, a regular life and family planning will be impossible.

Every person is entitled to his amount of energy.

- A vicious circle (on the one hand ... but on the other hand)

On the one hand: in the short term, we must hope for a sharp increase in global energy consumption, in order to improve living standards in the Third World and thus to contribute to a reduction in and eventually a stagnation of population growth there. Only in this way can the increase in energy consumption be stopped, since, whatever the case, energy consumption always depends on the number of people.

If it is difficult enough to predict world demographic developments; even more so to predict the development of future energy consumption and its consequences. What savings are we capable of or willing to make, what is the minimum required by the people of the Third World to free themselves from their undignified poverty? It would be self-deception if, pointing to similar developments in the industrialized world, one were to predict an end to the population explosion in the foreseeable future without at the same time calculating (and making available) the tremendous increase in energy consumption that would necessarily accompany it. Indeed, countless serious-minded scenarios have been worked out whose predictions vary dramatically, from a reduction by as much as half as a result of savings to an energy demand ten times that of today.

Let us ourselves attempt to speculate by how much present consumption, given the most favourable conditions, has to increase in order to achieve a constant final amount (we will exclude a reduction, which would mean permanent poverty and epidemics for three-quarters of the world's population): for argument's sake, we will assume that there is only one further doubling of the world's population, giving us 10 billion people. This is quite optimistic, for that number would already be achieved if the present population of the developing countries in southern Asia, Africa and Latin America increased two-and-a-half-fold, that of China and the other Asian planned economies one-and-a-half-fold, and that of the industrialized countries (including the Soviet Union and Eastern Europe) by a factor of only 1.2. This doubling of population would already mean a doubling of today's global energy consumption, provided that average pro-capita consumption were to remain the same as at present. However, this is only possible if we, today's large-scale consumers, drastically tighten our belts in order to allow developing countries more than previously and thus to raise their living standard and allow their increase in population to come to a standstill in the way that has been suggested. If, again extremely optimistically, we assume that it is sufficient to increase consumption in the quantitatively decisive developing countries of southern Asia and Africa threefold to a mere 1.3 kWa/a per capita (by which we would only be granting them one-third of our present consumption and one-eighth of America's), and equally threefold in China to today's average amount of 2.0 kWa/a per capita, and finally also granted the Latin American countries this average amount (which would only be 25% more than they have today) then all the highly industrialized countries, including the Soviet Union and Eastern Europe, would, by way of compensation, have to make do with 73% of what they consume today. They would have to adapt themselves to a 16% share of population and 34% share of energy, instead of today's 25% share of population and 75% share of energy! We Europeans would be left with 3 kWa/a each.

By way of comparison, and so that each of you can, according to mood, interpolate your own figure, here is the opposite calculation at what is probably the upper limit: if the world population were to treble to 15 billion people, and they all were to consume as much energy as we do today, i.e. 4 kWa/a (not 11 kWa/a like the Americans), then the final figure would be 60 TWa/a - six times today's global energy consumption!

The prediction that both present world energy consumption *and* present population will only double thus requires a degree of healthy optimism, especially if we consider how quickly the necessary changes in the world economy, with savings here and increases there, would have to take place and take hold. As I have said, the last doubling only took 35 years. If we only hesitate a little longer and therefore have to assume 12.5 billion people, but still do not want average per-capita consumption to rise, so that final consumption evens out at a figure 2.5 times higher than it is at present, then that will only be possible if the wealthy nations can make do with 60% of what they consume today instead of the 73% mentioned above. In fifty years time at the latest, then, the energy supply for the Third World will have had to have increased at least threefold.

On the other hand, however, we have learned - and this is where the vicious circle seems to close - that precisely this urgently required increase in energy production, however much it may be, will consume our already meagre reserves even faster than at present, and place a further burden on our environment. And above all: the problem becomes considerably more critical in view of the fact that this drastic increase in energy has to be generated in the countries of the Third World, which even today cannot afford the cost of environmental protection. They will therefore step up deforestation, burn their coal, spend their foreign exchange on oil, or seek their salvation in nuclear power - none of which, for them or for us, are solutions, but a dead-end.

We have to break out of this *vicious circle of poverty and environmental destruction*. To do so, we need a clean, safe energy source that is available for everyone in sufficient quantities. Only the industrialized countries have the means and the potential to develop this; they must therefore do so before it is too late.

We all live on and from the same earth.

THE ANSWER

We therefore need an energy source which is 1) inexhaustible, 2) environmentally sound, 3) available everywhere and 4) that everyone can afford.

The *fossil fuels* coal and mineral oil are exhaustible and polluting. Since, in addition, they usually do not occur in densely populated and low-earning countries, they also do not fulfil the last two above-mentioned conditions for everyone and, above all, for those countries where an increase in energy consumption is needed. As the transition to a new energy source which fulfils all these conditions costs a lot of money and energy, the task of today's sources of fossil fuel is to finance this transition. Once again, this shows that the countries which can afford today's cheap energy must develop the new energy sources, and that there is no time to lose.

Nuclear energy leaves the question of the first two conditions open. The third has been discussed above, but a positive answer was only possible in our case, if at all. The question of its profitability is still completely open; under no circumstances do we today pay its true cost via the electricity meter; in other words, its development, re-processing, disposal, environmental damage such as heating up of the air and of rivers, consequences of breakdowns, shutdowns, police protection, fear. While these "external costs" are estimated at at least half the market price in the case of conventional coal-fired and oil-fired power stations, there are no reliable figures available for nuclear electricity.

Renewable forms of energy, the direct or indirect utilization of solar energy, are the only energy source with a realistic chance of fulfilling all these conditions, albeit not without closer investigation. Renewable energy sources are really only inexhaustible when they are situated on useless terrain and when inexhaustible raw materials, such as sand and stone for glass and concrete, can themselves be used for the construction of solar power stations, and the requisite energy itself comes from renewable sources. Furthermore, their compatibility with the ecological and sociological environment must be tested in each individual case, as experience with large hydropower stations and tidal power stations has shown. As yet, however, there is no reasonable argument against large solar power stations in dead, empty deserts, which only take away a small proportion of local irradiated energy and thus influence the climatic balance far less than natural fluctuations in climate - unless one rejects all technological solutions out of hand.

As we are dealing here with global energy demand - in other words, with quite immense quantities of energy - we can restrict ourselves to a discussion of the large-scale utilization of solar energy as well as of the generation of electricity, since this allows it to be used in the most versatile way, including transport and storage.

This is not to underrate direct thermal utilization, either passively in buildings or actively via collectors to generate hot water or as process heat for industry; even here in Northern Europe, this can be a sensible local solution. We should equally not forget the indirect utilization of solar energy: at present, only about 10% of the economically feasible potential of hydro-electric power plants is being used worldwide (even so, that makes about 2% of the primary energy available). Nor should we forget wind energy, which has experienced a considerable boom over the past few years and which, in certain cases, has broken through the profitability barrier, but which is only suitable for small-scale consumers. Further sources are the utilization of glacial energy in Greenland, of tidal movements, marine warmth, wave energy and biomass.

Of the truly interesting new ways of generating large quantities of solar electricity, the atmospheric power tower (also called solar chimney) should be mentioned first. It has profited from experience with hydro-electric power plants, so far the only truly successfully used renewable energy source in modern times. It is no coincidence that both were developed by civil engineers: the "hydro-power plant of the desert" combines three known principles - the greenhouse to heat air, the chimney effect to generate an upward draught, and the windmill to generate electricity. The sun heats up the air under a flat, circular glass roof, in the middle of which is a vertical tube, open at the bottom. Entering this tube, the warm air creates an upward draught there. The draught drives a turbine with a generator. A prototype, in Manzanares in Spain, which was in operation without a break for three years - something which few other solar power stations have ever managed - confirmed the principle, the theory and the robustness of this type of power station. Accordingly, it would now be possible to construct power stations of this type with an output of 100 MW or more and, with them, to generate electricity in desert areas at a price of about 15-20 Pf (= US$ 0.075-0.10) per kWh. Its simple technology makes the atmospheric power tower ideal for countries of the Third World; it can be built and run there cheaply, using local labour. Its further development was more or less laid to rest years ago. The Manzanares plant literally fell apart for lack of funds for its maintenance. Why is the atmospheric power tower not being promoted and developed far more intensively?

Let us stay in the field of the utilization of solar heat. Using curved mirrors, there are several ways of concentrating sunlight to heat gases and liquids which then drive motors or turbines. If a whole field of mirrors, called heliostats, is concentrated on one focal point at the top of a tower, this is then known as a solar tower plant. So far, six of these have been built worldwide, the most important European one having been built with German collaboration in Almeria. However, it must be said that this has never managed to achieve truly permanent operation, let alone reach the profitability barrier. Only the widespread parabolic trough collector plants have managed this so far - at least in California, which in this respect has particularly favourable tax laws. Their mirrors are simply curved and panned, thus compensating for a relatively low efficiency factor with a simple technology, as is the case with the solar chimney. It is hoped to replace diesel engines for electricity generation in remote farms or mountain huts with parabolic mirrors which track the sun and in whose focal point "Stirling engines" generate electricity. Mirrors like this, combined with biogas burners, can be designed for permanent operation.

Hopes are being placed in solar cells, or photovoltaics. Without any movable parts, they convert light directly into direct current. Although still far from profitability today, this will probably be achieved in the course of their further development given better efficiency factors and mass production, for such modules can be manufactured fully automatically. As a result, however, this line of development fails to live up the criterion of providing employment in the overpopulated countries of the Third World.

First of all, of course, the attempt will be made to establish these solar power stations as close to the consumer as possible, and indeed, in the vicinity of large, sunny desert areas, there are countless densely populated settlements with a great energy demand, including many cities with a population of a million or more. Because these suffer from hour-long electricity cuts every day, an orderly life (not to mention industrial production) is hardly possible. Their peak loads could be covered directly with solar energy. Using today's solar technology, a direct utilization of this kind, without further transport and without storage, costs about 20 Pf/kWh and has thus already reached the profitability barrier, not counting the fact that this electricity can be generated there locally without the need for foreign exchange, and that it therefore creates jobs in these countries.

In principle, however, even countries with little sunshine and far away from deserts can be supplied with electricity from the desert without any problem. In this case, this high-quality (since it is versatile) electricity would be transmitted here directly via overhaed lines or undersea cables and used for the 70% of our present final energy demand that is consumed in a stationary manner; in other words, in industry and househoulds. From a technological point of view, high-voltage direct-current transmission (HVDCT) is fully developed. The Cabora Bassa HVDCT, for example, can transport 2000 MW over a distance of 1400 km. Even considerably greater distances can be mastered without technical difficulties. Transport losses are astonishingly small. For a 3500 km long cable from Africa to Germany, a loss of less than 15% has been calculated, with the possibility of reducing that figure still further. Furthermore, it is expected that the whole of Europe will be covered with an HVDCT grid within the next 20 years anyway, as part of an EC scheme. Then solar electricity from Africa could be fed into the European grid via Southern Europe at little additional cost. Compared to HVDCT, the use of super-conducting cables is still in its infancy.

With an HVDCT grid stretching over continents, differences in demand can be compensated very effectively, and this amounts to storage. Nevertheless, some storage of electricity will still be necessary, for which the time-proven, every low-loss (25%), cheap method of pumped storage is the obvious choice. During light-load periods, surplus electricity is used to pump water from a low-lying reservoir to a higher storage reservoir. During peak demand, the stored water runs back into the valley and drives a turbine with a generator. To date, batteries and flywheel accumulators have little chance in comparison; rather, there may be a chance for underground compressed-air storage power stations in suitable areas or, as a more modern development, for super-conductive coils.

It is clear that the question of whether storage is necessary is a determining factor as regards the cost of imported solar electricity. On average, an increase of roughly 10 Pf/kWh will have to be calculated for transport and the necessary storage; on that basis, with commercial application of the solar technology available today, it would be possible to supply solar electricity in Germany via a European HVDCT grid at a cost of about 30 Pf/kWh. This is the actual total cost; in other words, it includes the external costs that are usually disregarded in today's energy prices (see above).

Electricity is unsuitable for mobile consumption on roads and in the air; for the present at least, batteries are still far too heavy and too expensive. As already mentioned at the start, hydrogen technology is an obvious choice. Immediately at the solar power station, using the electricity generated there, water is split into its component elements hydrogen (H_2) and oxygen (O). The hydrogen is transported here in gas form in pipelines via Southern Europe or in liquid form, having been cooled to -235°C, in tankers via the North Sea. Here, with the help of appropriately re-equipped filling stations, car petrol tanks and automobile engines, it then takes over the role that petrol and diesel fuel have had up to now. All the technology alluded to in brief here is fully available, is controllable as far as safety is concerned and has been tested in numerous trial vehicles, even if it still can be considerably improved, especially as regards cost reduction and the space taken up by the tank. Hydrogen has long since become irreplaceable in space travel, and the German chemical industry has had an almost 1000-kilometer long hydrogen pipeline grid for many years now. Of course, the hydrogen produced in the desert with solar energy could be burned again for heating purposes and to generate electricity after having been transported here; however, the losses incurred would be too great in comparison with the direct transmission of electricity:

- in the efficiency chain of electricity (Sahara) - electricity transport - electric heating (Germany), there is a total loss of approximately 25%,
- in the chain of electricity (Sahara) - hydrogen (Sahara) - heating with hydrogen burner (Germany), however, this figure is approximately 40%. The following would be senseless:
- electricity (Sahara) - hydrogen (Sahara) - electricity from hydrogen (Germany) - electric heating (Germany), with a total loss of approximately 60%.

When hydrogen is burned with air the only pollutant is the NO_x that is emitted; however, this can be kept infinitely small in cars by setting a lean mix. This means accepting a loss of performance of about 20% in comparison with petrol-driven operation. Thus, in order to replace 1 litre of petrol, weighing 0.8 kg and with a calorific value of 9.7 kWh, the equivalent of 9.7/0.8 = 12 kWh are needed in the form of hydrogen; that is roughly 3.7 m^3 of gas or 5 l of liquid hydrogen, made from about 4 l of water, but weighing only 0.33 kg. For reasons of space, cars use hydrogen that has been liquified by cooling it down to -235°C and is kept in a thermally insulated tank. Nevertheless, this tank has to be considerably bigger than a petrol tank. The energy used to liquify the gas swallows up about a quarter of the energy in the hydrogen. This makes this clean fuel still fairly expensive by today's standards - about 5 DM for the equivalent of a litre of petrol. However, this picture will change very quickly if the cost of hydrogen falls as a result of technological improvements and large-scale commercial production, and if oil prices rise again and their external costs are counted, too.

Winter und Nitsch from German Aerospace Research Establishment (DLR) in Stuttgart, who have concerned themselves with this topic more than anyone else, and whose publications are the basis of much of what has been said here, have also looked at the economic effects and material requirements for the establishment and maintenance of solar-aided hydrogen production. They conclude that the necessary resources are available in the industrialized countries, but that the manufacturing capacity that will have to be provided for certain components will be greater than for comparable present-day industrial products. In view of the chronic levels of unemployment, that really ought not to frighten us.

The question remains - the question in the title - as to how much space is needed to utilize the sun as an energy source. The large amount of space needed for solar power plants is frequently cited as sufficient reason to disqualify the utilization of solar energy as unrealistic.

This is the result of the sun's low power density, which is only 1.35 kW/m^2 when it enters the earth's atmosphere, which in its turn absorbs and reflects a considerable part of that energy, depending on location and climate conditions. Here in Germany, the sun only shines for about 1300 to 1680 of the 8760 hours in the year, giving a mean annual irradiation of between 900 and 1100 kWh/m^2. The deserts of Africa, Arabia, America and Australia, because of their small amount of cloud cover and equatorial situation, receive roughly 2300 to 2500 kWh/m^2, which means that less than half as much space is needed there to procure the same amount of energy. It would therefore not make any sense to want to aim for large-scale utilization of solar energy in Gemany, which is densely populated and intensively cultivated. At present, in Germany, renewable forms of energy contribute only 2.4% to primary energy consumption; hydropower alone contributes 2%, and three-quarters of its potential are already being exploited. One would have to be extremely optimistic to imagine that, thanks to sun and wind and an altered economic situation, we could even tangibly cover our demand with local renewable energy sources to the extent, say, that nuclear energy does now (11%, compared with the 42% covered by mineral oil, the 19% by coal, the 17% by natural gas and the 8% by lignite).

No, if we really want clean and renewable solar energy, then we have to produce it in deserts and transport it here.

Of course, not every square metre of desert can be used. We need access roads and DC voltage changers (in the case of direct electricity transmission with HVDCT) or electrolyzer outfits (in the case of hydrogen production) between the circular glass roofs of the atmospheric power towers. This would give a surface utilization of about 80%. On the other hand, this solution can only convert about 2-3% of the energy irradiated onto this surface into electricity. While solar cells make worse use of this surface (by about 50%), because their mounting frames, which are inclined towards the sun, have to be kept some distance away from each other so as not to put the others in shadow, they have a better efficiency factor of 10%. In the case of the parabolic mirror plants, also described above, surface utilization is reduced to 15%, while the efficiency factor increases to 25%. As it is at present still undecided which type of solar power station will eventually generate electricity most reliably and most cheaply, we will take the mean product of the degree of surface utilization and respective efficiency factor as the basis of our calculations; in other words, roughly 0.033. If we multiply this by the average annual irradiation of a square meter of desert (2300 kWh/m^2), and multiply the whole by a further 0.8, representing transport losses during the 3500 km journey from the Sahara to Germany (which, for simplicity's sake, we will regard as the same for electrolysis and hydrogen transport as for direct electrical transmission), then we get 2300 x 0.033 x 0.8, or 60 kWh/m^2 per annum, or - since 12 kWh are the equivalent of 1 litre of petrol, as has been explained above - 60/12 = 5 litres of petrol.

We therefore need one square metre of desert for 60 kWh of electricity or 5 litres of petrol per year.

For his 15,000 km in Germany (or 1500 litres of petrol), then, our car driver needs 1500/5 = 300 m^2 = 3 ares of desert. Really that little!

(Incidentally, it is worth thinking about the fact that these 1500 litres of petrol, or 1500 x 12 = 18,000 kWh swallow up roughly half of the average German per capita consumption of 4 kW x 365 days x 24 hours = 35040 kWh).

In 1987, the Federal Republic of Germany consumed 41,222 million tonnes of petrol and diesel fuel, the equivalent of 483 billion kWh/a or 0.055 TWa/a, which would require 8000 km^2 of desert. Our total final energy demand of 0.24 TWa/a could be procured from 35,000 km^2 or 0.38% of the surface of the Sahara; consequently, the present global final energy demand of some 7 TWa/a (see footnote p. 5) could be procured from no more than a good tenth of the surface of the Sahara!*** Yes, that is astonishingly little, at least from a relative point of view; in absolute terms, it is of course a huge area.

The area required is therefore no argument against the utilization of solar energy. All the world's countries can be supplied from today's unexploited deserts, even if global energy demand doubles or trebles.

To sum up: the state-of-the-art in solar energy utilization has now reached a level which permits us to state confidently that a commercial utilization of the sun is feasible. The world's deserts offer sufficient collector areas, while transport of this energy from the deserts to the consumer is now no problem, either. Solar energy is therefore available everywhere and for everyone. Today, we could bring solar electricity from the desert to Germany for 30 Pf/kWh. This is not too much at all compared with other energy sources if their subsequent or external costs are taken into account.

THE NEXT QUESTION - WHAT IS THE ANSWER?

In view of the magnitude of the threat and of the answer that solar energy could provide, the bewildered question arises as to why much more is not happening in this direction.

Of course, the cost of solar-generated electricity is still quite high at present, and many a man may think the prices quoted as attainable here still too optimistic. But whoever shares concern for our environment, together with concern for the population explosion and Third World poverty, should not simply counter with "too expensive" or even "cranky" when someone claims that "solar energy is the answer", but demand that evidence or counter-evidence be provided or help provide that evidence.

Generally speaking, what commercial utilization of solar energy needs today is practical trials on a realistic scale; only these would allow irrefutable conclusions to be drawn about its reliability and cost. It would also still be too early to play off one technique against others; rather, development should be continued across the whole scale. Most of the plants that have been built to date are toy-size and frequently serve as an alibi for politicians and utility companies. Many interesting approaches suffer as a result of bureaucratic and financial obstacles. Whoever works in this field has to be constantly on the defensive and fight, rather than receiving support and being able to think ahead.

The fact that development in this field has not progressed much further to date is not the fault of scientists' or engineers' lack of ideas or commitment, but of half-hearted support which does not allow for any planning and is inconsistent. Even here, then, one has to fear that many a hard-fought success will get bogged down again for lack of funds.

At this juncture I would like to deny emphatically the contention that solar energy research is generously and sufficiently supported by the state or, moreover, that the available funds are not even applied for. If the latter has been the case then this was only because applications are at present only approved if they can show a considerable financial contribution on the part of industry itself. However, this cannot be expected of companies which, in the mid-term at least, have to find profitable markets. Furthermore, such a grants policy is devoid of any pur-

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*** Of course, it would not make any sense to extract every country's energy from the Sahara instead of making use of the nearest desert in each case. At the same time, when calculating total area by means of this simple projection, we have to assume that the average global consumer is just as far away from "his" desert as we are from "our" Sahara in order to estimate transport losses correctly. To cover the demand of the Sahara's "neighbours" in Europe and Africa, including Turkey and the entire Soviet Union, about 4 % of the Sahara would suffice.

poseful bias and leaves things to chance. Solar energy technology and the global protection of the environment which goes with it are part of the state's duty to provide for its citizens. Of course, high tech, from outer space to the chip, is more glamourous, but the broad mass of the population is today more concerned with the environment than with progress at all costs and, furthermore, is prepared to make sacrifices. Nobody would protest at an increase in funds for research into renewable forms of energy; on the contrary, young people especially long for a challenging task for the future.

In 1988, the German Federal Ministry for Research and Development made just DM 135 million available for research into renewable sources of energy. Altogether, one mere billion was spent between 1974 and 1987. Over the same period, coal and oil received 3.5 billion and nuclear energy almost 20 billion; it is scarcely imaginable where the exploitation of solar energy would be today if it had received anything like as much in the way of support. This relationship is distorted still further if one considers that the sums mentioned for renewable sources of energy also include the actual construction of the solar plants, while in the case of nuclear energy, the money was in the form of true research funds. Astronomic sums were needed just to shut down nuclear power stations. By way of comparison, it is interesting to note that the German Federal Environmental Protection Agency estimates annual depreciations as a result of environmental damage at some DM 100 billion.

One does not even dare hope that, as a result of the replacement of the perennial military-territorial fight for supremacy by an international scientific-economic struggle for power, a small part of the West German DM 55 billion defence budget might find its way into the promotion of renewable sources of energy. Poor and overpopulated countries, including and above all the Soviet Union, have realized that they will lose the international economic race as well as the fight against their increase in population if, at the same time, they have to arm. We should have the courage to help them, and not to force them to wall with our technology and our wealth. This would be particularly fitting for us Germans.

Above all, we have to hurry because the population explosion in the Third World is driving energy consumption to immeasurable heights. The increase in population can only be stopped by an increased standard of living which will, at first, require more energy. Energy savings here can and must soften the impact of this increased consumption in the Third World, but they cannot absorb it completely. In view of the periods of time needed today for development, permission, construction and amortization, investment decisions are needed right now that are trendsetting and imaginative.

Admittedly, it takes some imagination to picture the transition to an economy based on solar energy at all, and within a few decades at that. But could we have imagined the development of the car, the aeroplane, telecommunication, or the explosion in GNP fifty years ago? Of course, large-scale investment and economic effort will be needed to achieve it, but if this is done gradually it should not exceed the amount that we spend on energy and transport at present. And as has been said, why should we be frightened of challenges and the chance of thus getting rid of unemployment, and why should we not make sacrifices once again, and do without this or that? The older generation will remember that the hard times immediately after the war was not all bad.

Of course, a solar energy industry also needs long-term treaties with the sunny desert countries, somewhat like the natural gas agreement that was drawn up many years ago in spite of ideological barriers. Furthermore, nothing could contribute better to a permanent guarantee of peace than mutual dependence and a closing of the North-South gap. Today's oil-producing countries, which are usually also sunny countries, could in this way permanently secure their energy exports, and should therefore be prompted to join in the establishment of the solar energy industry. Today's sunny countries which are lacking in raw materials could create themselves a new economic base. Would it not be better to help them to help themselves, rather than giving them loans on which they cannot even repay the interest? A high degree of perversion was recently reached with the offer of debt write-offs in return for environmental protection. These countries are only felling their rain forests because they have no other alternative and because we have neither developed the method of obtaining solar energy nor tested it out with them in their countries.

May politicians recognize the potential of the utilization of solar energy, accelerate its development through increased support and prepare the way for it through international treaties!

Conclusion

The only answer to the greatest threat in the history of mankind - the population explosion with undignified poverty in large areas of the world and, as a result of that, climatic and environmental catastrophes all over the world - is a clean, safe source of energy available in sufficient quantities for all of mankind. It would be both technically feasible and affordable, and a fraction of the earth's desert areas would be enough to obtain from solar radiation the amount of energy needed to avert these catastrophes. Mankind and nature will benefit from each additional percent of our energy demand we draw from the sun.

Why are the necessary steps not finally taken to develop fully the technology needed for solar energy exploitation? Even sceptics ought at least to risk investing the relatively small amount of money needed to substantiate or invalidate the claims made of this technology.

It has to be said that unparalleled material and political effort will be needed to gradually bring about a solar economy. To face up to this challenge and to demand this effort of society can be said to be a matter of paramount political urgency.

Postscript

The author, being himself a structural engineer, came to write the above paper through his own work in the field of solar energy utilization. He learned from there how immensely difficult it is to raise funds for research and development in a field where industry cannot expect direct profits and which does not immediately open a market, but which needs a long breath. He knows that government people make decisions not based on facts or needs as such but on the public's perception of the facts.

This paper was first written, as one may have noticed, to lay the mind of German readers, especially politicians. It received quite some consent - the time is ripe for such thinking and for action! - but also doubtful questions. As already expressed in the paper itself, the author shares the scepticism of those most elderly correspondents. Of course he is aware that this world will never again, as it did before, see a pure renewable energy scenario. But isn't the cause worth to approach it even with dreams? (Didn't exactly the German political scene demonstrate recently that dreams may become true?) If only part of the world's energy need and exactly that part in the Third World which cannot and which should not be covered otherwise, would be satisfied by solar energy, the dream would already have become true. And who would be so stubborn or biased not to be ready to accept simultaneously any other energy source including nuclear, if it should some day satisfy all requirements? What could be more provoking and worthy for scientists and engineers than to compete on these grounds and to praise any success?

In that sense the author wants to thank Prof. J. Schneider, chairman of the editorial board of IABSE for inviting the publication of this paper, and for suggesting to supplement it with a short technical report on two devices producing electricity from solar radiation, in whose development the author was involved.

Atmospheric power towers or solar chimneys (see also page 8 above)

In the solar chimney, three well-known physical principles - the greenhouse effect, the chimney, and the turbine - are combined in a novel way (Fig. 1). Incident solar radiation heats the air under a large collector roof. The temperature difference causes a pressure drop over the height of the chimney resulting in an upwind which is converted into mechanical energy by a turbine and then into electricity via a conventional generator. This solar energy system has many technological and physical advantages:

1. It makes use of global radiation, including diffuse radiation when the sky is overcast.
2. The natural storage medium - the ground - guarantees operation at a constant rate until well into the hours of darkness (and throughout the night with large-scale installations).
3. Aside from the turbine and generator, there are no moving parts or parts that require intensive maintenance. No water is required to cool mechanical parts.
4. It features a simple, low-cost design utilizing know-how and materials that are also available in Third World countries (glass, concrete, steel). A high proportion of the costs is accounted for by work that is simple. This would benefit the local labour market while at the same time helping to keep overall costs down.

With assistance from the German Federal Ministry for Research and Technology, an experimental facility was developed and built in Manzanares, Spain (Fig. 2) where these advantages are documented by a high degree of availability of the plant and low operating and maintenance costs.

Fig. 4 shows the hours of daily service for a full operating year. To permit a comparison, the measured hours of sunshine with over 150 W/m^2 irradiation and the theoretically possible maximum number of hours of sunshine (from sunrise to sundown) are also shown. The analysis revealed that, for example, in 1987 the plant was in operation for a total of 3197 hours, which corresponds to a mean daily operating time of 8.8 hours. As soon as the air velocity in the chimney exceeds 2.5 m/sec, the plant starts up automatically and is automatically connected to the public grid.

These results show that the components are highly dependable and that the plant as a whole is capable of highly reliable operation. The thermodynamic inertia is a characteristic feature of the system, even abrupt fluctuations in energy supply are effectively cushioned. The plant operated continuously even on cloudy days, albeit at reduced output.

Using a thermodynamic simulation program, the theoretical performance of the plant was calculated and the results compared with the measurements obtained, showing that there is good agreement. Overall, it may be said that the optical and thermodynamical processes in a solar chimney are well understood and that models have attained a degree of maturity that accurately reproduces plant behaviour under given meteorological conditions.

Extrapolation of these results to larger plants produces the results summarized in Fig. 5. It shows the energy costs as a function of the size of the plant, expressed by the 24 hr-average power output. The height of the chimney (first figure) and the approximate diameter of the collector roof is given along the curves. Further parameters are the climate or location, where Almeria, Spain, with approx. 2100 kW hr/yr and Barstow, California, with approx. 2600 kW hr/yr are compared, because of these two places all meteorological data are available. With the same plant specifications, for example, a chimney height of 445 m and collector radius of 555 m, it would generate approximately 7.1 kW hr/yr under Almeria conditions, and 11.6 kW hr/yr, that is approximately 38 % more, in a climate such as that in Barstow, California. The calculations were based on a chimney life of 20 or, respectively, 40 years, while the life of the mechanical equipment and roof was assumed to be 20 years; purely theoretically, therefore, the roof and machinery could be replaced in the twenty-first year. The specific electricity generating costs were calculated by the real present value method (with a real discount rate of 4% and a depreciation period of 20 or 40 years.

The economy of the power plant is dictated by the investment necessary to construct the plant and operating costs; these comprise personnel costs, maintenance and repair costs, and the cost of the necessary fuel. The calculations show that this power station technology, based on a renewable form of energy, satisfies every precondition for continuing development: technically feasible potential combined with power generating costs that, conservatively estimated, will be below \$0.10/kW hr.

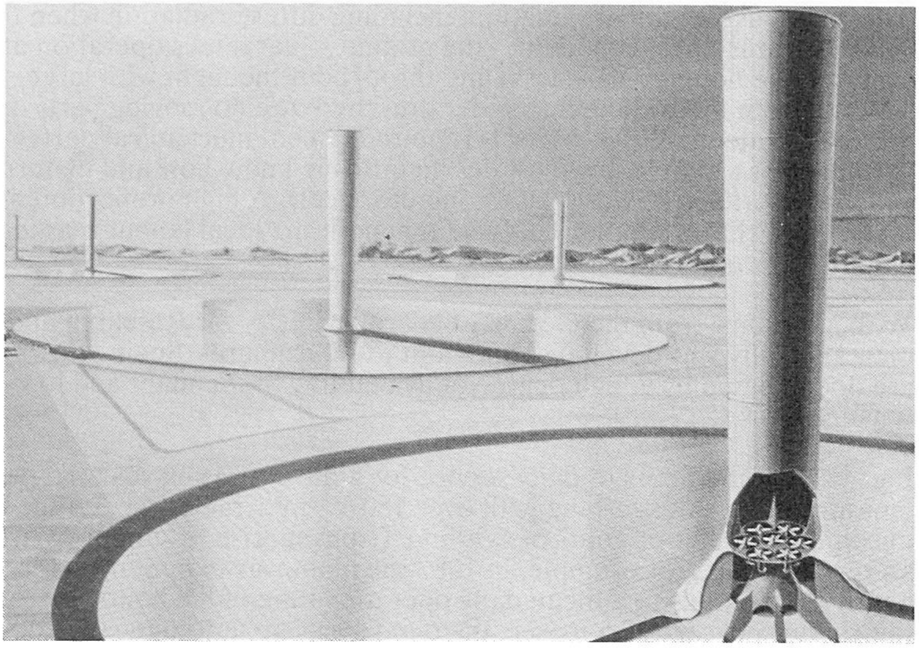


Fig. 1: Drawing of several large solar chimneys in the desert

Fig. 2: Aerial photograph of the experimental facility at Manzanares, Spain (height of chimney 200 m; chimney radius 5 m; collector 120 m/120 m; rotor diameter 10 m; nominal speed 100 rpm)

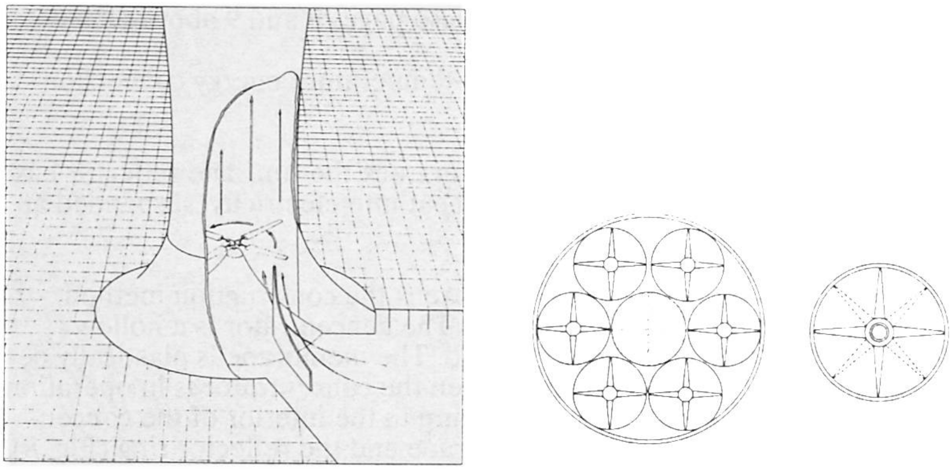


Fig. 3: While smaller units can operate with a single wind turbine, larger power plants would work better with several turbines. During operation, automatically controlled setting gears adjust the blades to their optimal face-impact angle.

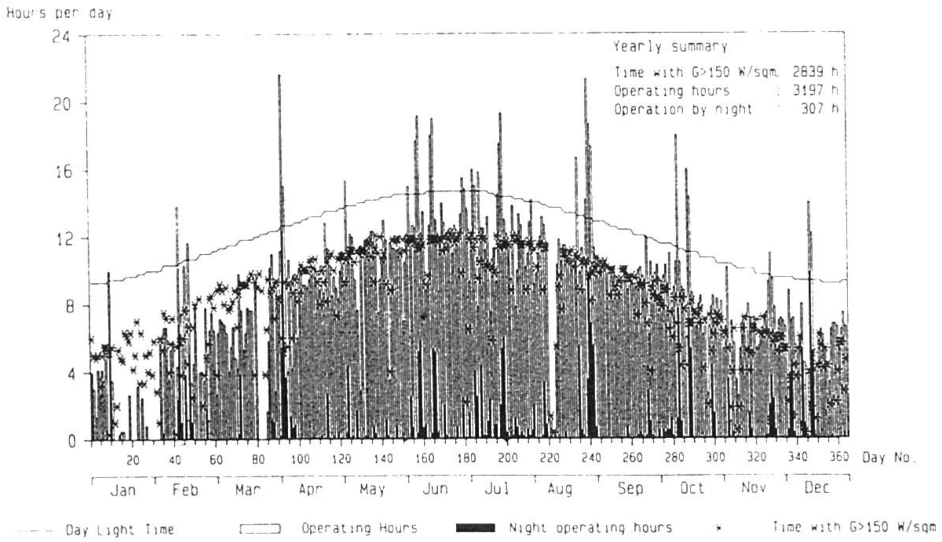


Fig. 4: Plant operating hours for 1987 of the solar chimney in Manzanares, Spain.

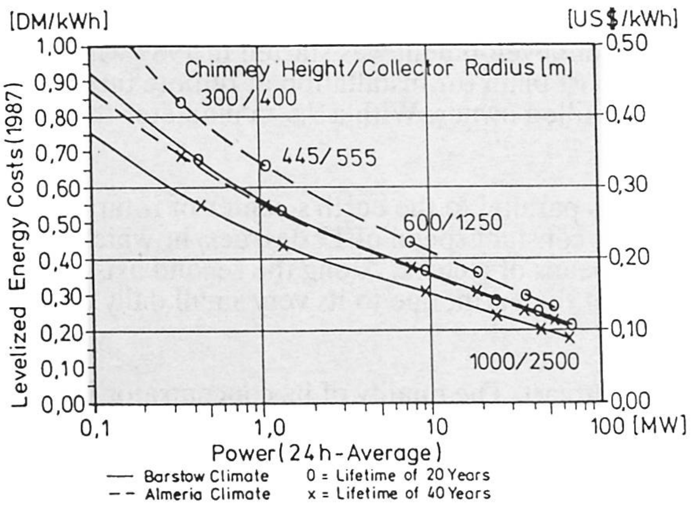


Fig. 5: Solar chimneys' electricity generating costs in relation to mean installed power.

Solar power plant with metal membrane concentrator (see also pages 8 and 9 above)

As a means of generating electricity from solar energy, high-temperature energy conversion with concentrating systems has a very promising future.

A large hollow reflector is suspended in such a way that it can track the sun. The reflector has an energy converter, which converts the concentrated solar heat into electricity, suspended at its focal point.

The new and special feature of the power plant described here is the construction method, which makes a very large and precise concentrator possible. The concentrator is a hollow membrane of thin sheet steel to which mirror glass is bonded. The membrane is plastically deformed to the desired paraboloid shape by air pressure. When the concentrator is in operation the shape of the membane is kept constant by a partial vacuum in the interior of the concentrator, i.e. between the reflector membrane, the rear membrane and the reflector ring (Fig. 8).

The energy conversion system (ECS) consists of a Stirling engine with a receiver located at the focal point of the reflector; the reflected solar rays heat the working gas (hydrogen) of the engine. There is a generator coupled directly to the engine.

Since each unit is capable of fully independent operation, as many concentrators as desired can be operated in conjunction, according to requirements. They can be operated both in grid connection mode or "stand-alone" mode. Storage devices (batteries, pumped storage etc.) may be provided or a hybrid conversion in combination with gas.

Power plants with reflector membranes are capable of an overall efficiency (defined as the ratio of the output usable electricity to the solar irradiation over the reflector surface) of up to 27%. This has never been achieved with other types of solar plants. As the membrane construction method used for the reflector is relatively inexpensive they also make economic electricity generation a real possibility. The output of the energy converter depends on the accuracy of the beam path. The reflector membrane satisfies this requirement, though only a simple technology is needed for its fabrication. With carefully planned technology transfer such power plants could therefore also be fabricated in the low-income countries of the Third World.

In 1985, after constructing a test facility in Germany, two concentrators with 17 m diameter were installed in Saudi Arabia (co-sponsored by the King Abdul Aziz City for Science and Technology in Riyadh), (Fig.6). Their power output is 50 kWe each. After the "usual" initial problems, especially with the Stirling engines, both are now continously operating according to expectations.

With the experience such gained, a further step of development was started in 1987 with the goal to develop a smaller size and extremely robust plant for installation at remote farms or other remote places and for operation by its unskilled owner. With a 7.5 m diameter the power output is 9 kWe.

This concentrator is polar mounted with one axis parallel to the earth's center of rotation. Thus, tracking of the sun may occur at an almost constant speed of 15 degrees/hr which can be achieved without electronic aid but only by means of a clock. Along the second axis the necessary adjustment is prescribed by the ecliptic of the earth; due to its very small daily changes it can be operated discontinuously and manually.

A test facility of that sort is now operating in Stuttgart. The quality of its concentrator is extremely good since a concentration factor of at least 10,000 was measured (Fig. 7). Thus the main aim of future development must be to build Stirling engines in series. It is also intended to reach a 24 hours operation of such plants by combining it with a bio gas installation.

Finally it should be mentioned that such metal membrane concentrators are also capable to make extremely precise and economical heliostats for the so-called solar towers (see also pages 8/9 of the above paper).

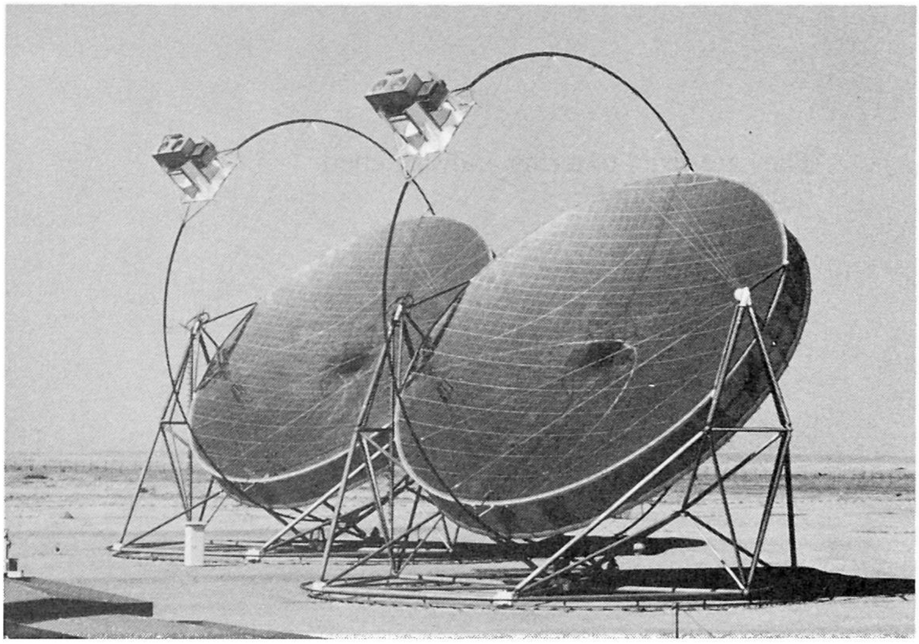


Fig. 6: Two 50 kWe concentrators in Riyadh (azimuthal mounted)

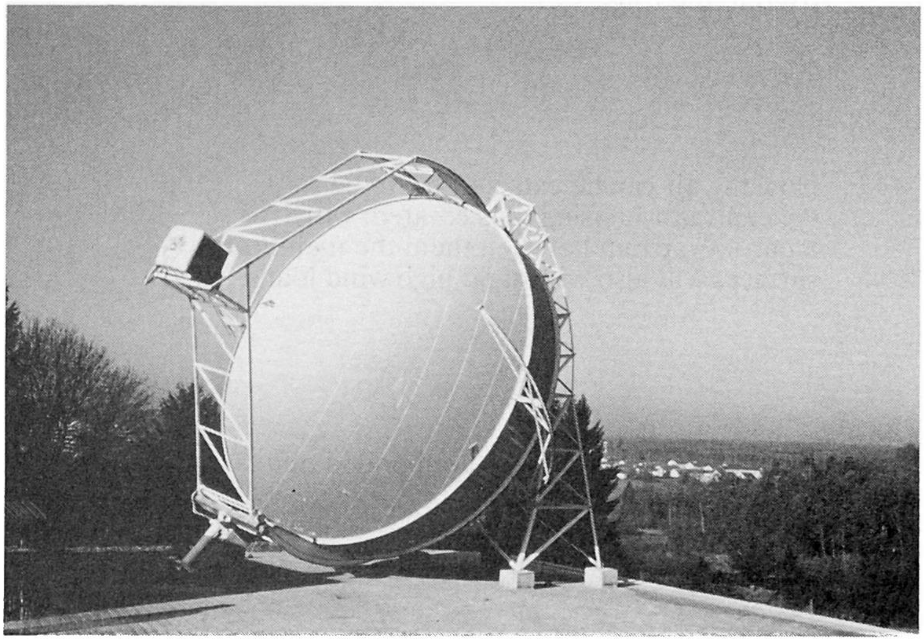
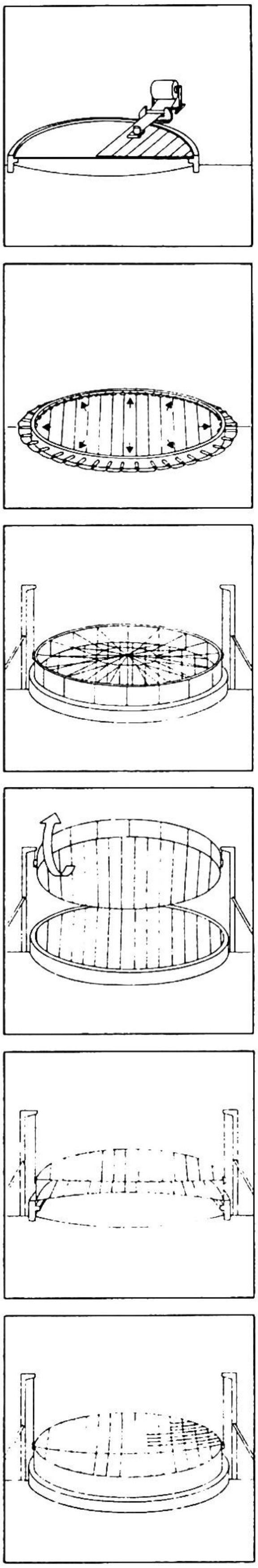


Fig. 7: 9 kWe concentrator in Stuttgart (polar mounted)



The membranes are made of individual sheet-metal strips welded together in the same plane with a welding device specially developed for thin sheet metal, which insures a gastight seam.

They are fixed to a ring and stretched radially until flat.

After fixing the rear membrane to the ring the concentrator is turned over.

The front membrane is then deformed to a paraboloid by applying air pressure between the membrane and the ground and subsequently fixed to the ring.

Now the air can be extacted from the concentrator housing thus created: with a partial vacuum between them the membrane surfaces will also withstand high wind loads.

Finally, thin glass mirrors are bonded onto the front membrane.

Fig. 8: Fabrication of the concentrator housing